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Comparison of carbon dioxide and nuclear waste storage costs in Lithuania

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ABSTRACT

Nuclear power and carbon capture and storage (CCS) are key greenhouse gas mitigation options under consideration across the world. Both technologies imply long-term waste management challenge. Geological storage of carbon dioxide (CO_2) and nuclear waste has much in common, and valuable lessons can be learnt from a comparison. Seeking to compare these technologies economic, social and environmental criteria need to be selected and expressed in terms of indicators. Very important issue is costs and economics of geological storage of carbon dioxide and nuclear waste. The costs of storage are one of the main indicators for assessment of technologies in terms of economic criteria.

The paper defines the costs of the geological storage of CO_2 and nuclear waste in Lithuania, drawing also on insights from other parts of the world. The costs of carbon dioxide and nuclear waste storage are evaluated in UScnt/kWh and compared. The paper critically compares the characteristics and location of the both sources of and storage options for CO_2 and nuclear waste in Lithuania. It discusses the main costs categories for carbon dioxide and nuclear waste storage. The full range of potential geological storage options is considered and the most reliable options for carbon dioxide and nuclear waste are selected for the comparative costs assessment.

Contents

1. Introduction

Carbon dioxide storage and nuclear energy are among the most viable GHG emission options. Carbon dioxide and radioactive waste storage are undertaken as the final stage of fossil fuel nuclear energy chains. Technologies are being called as back-end technologies.

According to the UNFCCC Kyoto protocol signed by the Lithuania in 2002, the level of greenhouse gases emissions should be reduced by 8% during the commitment period 2008–2012 compared to the 1990 level. Compared to 1990, the greenhouse gas (GHG) emissions in Lithuania currently are more than 50% bellow year 1990 level. However the final closure of the Ignalina NPP which was the main sources of electricity generation in Lithuania in 2009 and forthcoming new international climate change mitigation regime since 2013 urge to evaluate different options of reducing CO_2 emissions, including the assessment of the geological CO_2 storage potential

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and construction of new nuclear power plant in Lithuania. For both these climate change mitigation options in energy sector – geological storage of nuclear waste or CO_2 is the key element however these back end issues are related with the highest uncertainties. Therefore it is important to carry out comparative assessment of these two back-end technologies in Lithuania. Comparative assessment means economic, social and environmental assessment of these two technologies. The most important assessment component is related with economics and costs assessment.

The aim of the paper is to assess and compare carbon dioxide and nuclear waste geological storage options in terms of costs. The main tasks to achieve this target are:

- To review literature on analysis of nuclear waste and carbon dioxide geological storage costs.
- To present comparative assessment framework for back-end technologies assessment.
- To describe nuclear waste and carbon capture storage options in Lithuania and to select the most feasible one.
- To defined nuclear waste and carbon dioxide geological storage cost components and to assess them for Lithuania.
- To compare total carbon dioxide and nuclear waste costs in Lithuania.

2. Review of literature on carbon dioxide and nuclear waste geological storage costs

There are several studies conducted for comparative assessment of costs of energy technologies. In some studies the costs of back-end technologies are assessed in terms of life cycle costs.

The most comprehensive study on comparative carbon dioxide and nuclear waste geological storage costs assessment was conducted by IAEA experts [1]. F. Toth and A. Miketa present the in-depth review of costs of geological disposal of carbon dioxide and radioactive waste all over the world.

Taking into account fact that just few countries have developed geological nuclear waste and carbon capture storage projects there is a lack of comprehensive and comparable data on nuclear waste and carbon dioxide storage costs.

Some studies compare the costs of the main energy technologies to reduce GHG emissions from energy systems. The life cycle electricity costs are assessed for fossil fuel based electricity with carbon capture and storage and nuclear [2].

Levelised costs of electricity generation costs were assessed for the new power generation option in 2015 and 2040 including various fossil fuels with CCS options and nuclear however the costs of CO_2 and nuclear waste storage were not distinguished in these assessments [3]. There are several EU funded projects dealing with assessment of energy technologies: EUSUSTEL [4], NEEDS [5], CASES [6], and PLANETS [7]. In all these projects energy technologies were assessed. The economic dimension of energy technologies assessment is based on average levelised electricity generation costs. In these studies advanced electricity generation technologies including fossil fuel based with CCS and nuclear were assessed.

Currently the format, content and practice of cost estimates for geological storage of nuclear waste and carbon dioxide vary considerably both within and between countries. Especially great difference exists in nuclear waste final disposal costs assessments. The reasons are largely due to different legal requirements in different countries and to historical custom and practice.

There are no accepted reference values for costs for investing into carbon storage facilities. In literature, the range for expected investment expenditures varies remarkably. Studies dealing with this topic show that investment costs for carbon dioxide storage depend on the disposal concept, geographical position and whether the exploitation is offshore or onshore. According IPCC [8] these costs lie in between 0.5 and 8 USD/t of CO_2 stored excluding potential; revenues from EOR or ECBM. The IPCC report presents the different estimates of storage costs for saline aquifers for different regions of the world. For Europe onshore from 1.9 USD/t CO_2 to 6.2 USD/t CO_2 and offshore from 4.7 USD/t CO_2 to 12 USD/t CO_2. The JRC Report [9] and McKinsey & Company study [10] presents the similar cost estimates for CO_2 storage – 4–12 EUR/t CO_2 (for injection depth of 1500 m). The POYRY study presents the range of CO_2 storage in UK. These costs may vary between 1 £/t CO_2 and 20 £/t CO_2 [11].

In International Energy Agency report [12] the CO_2 storage costs in saline aquifers for Europe ranges from 10 USD t/CO_2 to 25 t/CO_2 depending on disposal concept.

The ECOFYS study [13] presents detailed analysis of CO_2 storage costs for specific disposal concept and depending on depth of storage. The CO_2 storage costs are in range from 1.8 EUR/t CO_2 to 11.4 EUR/CO_2 [13].

The Global CCS institute in Australia gives Economic Assessment of Carbon Capture and Storage Technologies [14,15]. According this study the initial site finding costs and characterization represent a significant risk to the project and can increase storage costs from US$ 3.50/t CO_2 to US$ 7.50/t CO_2, depending on the number of sites investigated. Reservoir properties, specifically permeability, impact the ease that CO_2 can be injected into the reservoir and the required number of injection wells. Reservoirs with high permeability can reduce storage cost by a factor of 2 to below $5/t CO_2 over reservoirs with lower permeability. The costs of storage make 5–6 USD/kWh. According latest updates of Global CCS [16] the costs of storage makes from 3 to 8 US$/t CO_2.

EU GeoCapacity project [17] assessing European capacity for CO_2 storage provides assessments of CO_2 geological storage potential in EU member states. The costs of CO_2 storage range from −0.7 to 0.8 EUR/KWh.

There are several studies on CO_2 storage costs conducted in USA. The Study of Pacific Northwest National Laboratory presents 15 USD/t CO_2 costs for CO_2 transport and storage [18] The S.T. McCoy from Carnegie Mellon University [19] presents in-depth analysis of carbon dioxide capture and storage costs and develops the cost model based on storage parameters for their assessment. The sensitivity analysis indicated the total costs from 0.32 to 31.3 USD/t CO_2 stored.

Alstom Power in recent study [20] presented cost assessment of fossil power plants equipped with CCS. The costs of storage were integrated in total costs of fuel cycles.

Recent study by European Technology platform for Zero Emission Fossil Fuel Power Plant [21] indicated that there is a wide cost range due to natural variability between storage reservoirs (i.e., field capacity and well injectivity) and only to a lesser degree to uncertainty in cost elements).

Department of Energy and Environmental Protection Agency of USA [22–24] have developed comprehensive model for costs assessment of geological sequestration costs for United States. The following disposal concepts were analysed: non-basalt saline reservoirs, depleted gas and oil reservoirs, EOR, ECBM, gas shale and basalt reservoirs. The following cost categories were assessed for disposal concepts mentioned above: geological site characterization, area of review and corrective actions; injection well construction; well operation; financial responsibility; closure and post-closure care, mechanical integrity test and monitoring. This study can be used as reference for developing raff cost estimates for carbon storage projects in other locations.

In Table 1 the costs of CO_2 storage are generalized from different studies for specific disposal concepts.

Table 1
Carbon dioxide storage costs per tonne of CO_2 stored.

Disposal concept	IPCC (2005)	JRC (2009)	McKinsey & Company (2008)	Poyry Energy Consulting (2007)	IEA (2008)	Ecofys (2004)	PNW National Labora-tory (2008)	EU GeoCapacity (2009)	Global CCS institute (2009)	Mc-Coy (2009)	EPA (2010)
Saline aquifers on shore	1.9–6.2 USD/t	4–12 USD/t	4–12 USD/t	1 £/t	10–20 USD/t	1.8–5.9 EUR/t	20 USD/t for transport and storage	−4.7 to 22.2 EUR/t	0.2–5.1 USD/t	0.32–31.3 USD/t	3.54 USD/t
Saline aquifers of shore	4.7–12 USD/t			1 £/t	10–20 USD/t	4.5–11.4 EUR/t			0.5–30.2 USD/t		
Depleted gas onshore				1–20 £/t	10–25 USD/t	1.1–3.6 EUR/t					4.28 USD/t
Depleted gas off shore				1–20 £/t		3.6–7.7 EUR/t					
Depleted oil onshore					10–25 USD/t	1.1–3.6 EUR/t					3.19 USD/t
Depleted oil offshore						3.6–7.7 EUR/t					
EOR onshore	0.5–8 USD/t excluding revenues				15–25 USD/t	−10 to 10 EUR/t			−30 to 21 USD/t		28.12 USD/t excluding revenues
EOR off shore	0.5–8 USD/t excluding revenues					−10 to 20 EUR/t					
ECBM onshore	5–8 USD/t excluding revenues				15–25 USD/t	0–30 EUR/t					7.29 USD/t excluding revenues
Shale gas onshore											5.87 USD/t
Basalt onshore											USD/t

A wide variety of approaches are applied to the development of nuclear waste storage cost estimates. The cost studies were performed for the following nuclear waste repositories: Yucca Mountain in USA [25–27]; the final nuclear waste repository Olkiluoto and Loviisa in Finland [28,29]; final nuclear waste repository Forsmark in Sweden [30–32]; Belgium [33]; Japan [34], UK [35] and EU [36].

In Yucca Mountain the total repository costs make 96,180 mill. USD (in 2007$). The detailed cost structure is presented ranging from repository development to closure and monitoring costs. In DOE cost study for low level radioactive disposal facility in Texas [26] the total costs amounts to 142 mill. USD (in 2007$). The total costs of nuclear waste storage repositories in Finland make about 4122 mill. USD [28]. They are more than 20 times higher than in Yucca Mountain. In Sweden total costs of nuclear waste storage amounts to 5728 USD and are similar to Finland's estimates [30]. In Belgium the costs of a deep disposal facility were assessed for reference site (Boom Clay beneath the Mol-Dessel nuclear zone). The total costs amount to 2035 mill. USD and are more than half lower than for Finland and Sweden [33]. In Japan the final disposal costs were estimated for soft and hard rocks. The average costs for both rock types make about 33 bill. USD and are almost half lower than for Yucca Mountain [34]. In UK total costs are estimated based on Swedish repository concept (KBS-3) at approximately 9 bill. USD [35]. The SAPPIERR II project with the participation of 14 EU member states developed costs estimates for multi-national common repository. Three disposal cost assessment models were applied: the Swedish, Swiss and Finish. The total costs according Swedish and Finish cost models make approximately 9 bill. EUR and more than 10 bill. EUR according Finish cost model [36]. OECD report on harmonization of decommissioning cost estimates [37] has studied cost estimation practices in 12 countries and made conclusions that standard reporting template needs to be developed onto which national cost estimates can be mapped for the purpose of national standardisation and international comparison. In Table 2 the nuclear waste storage costs were generalized from various studies according specific cost items.

3. The framework for comparative assessment of carbon dioxide and nuclear waste storage technologies

There are several frameworks developed for energy technologies assessment based on economic, social and environmental indicators [38,39]. Back-end technologies can be evaluated by calculating the performance indicators based on data bases and assessment studies performed. Indicator selection determines which aspects are included in the evaluation and how they are considered. Decision making involves ranking of back-end technologies and selecting the best one based on the evaluations made earlier with life-cycle and uncertainty point of view [40]. The policy development and decision is based on multi-criteria analysis. Several methods can be applied for this purpose. Therefore the proposed framework for nuclear waste and CO_2 storage comparative assessment consists of 4 main areas: technical performance, social performance, environmental and human health impact and economic feasibility. The main indicators are presented in Table 3.

As one can see from Table 3 some indicators are quantitative and some qualitative. Quantitative indicators need surveys to be assessed. The quantitative indicators can be evaluated based on data bases and various assessment studies results. The major challenges are associated with separation of life cycle data for CO_2 and NW storage phase in full nuclear and fossil fuel with CCS chain. The developed framework of indicators can be applied for comparative assessment of nuclear waste and CO_2 geological storage technologies in Lithuania. These indicators can be assessed just having the

Table 2
NW storage costs, mill. USD.

Country	United States	Finland	Sweden	Japan	Belgium	UK	EU
Reference studies	OCRWM [25]. Analysis of the total system life cycle cost of the civilian radioactive waste management programme	Palmu [29]. Summary of the Cost Estimate for Spent Nuclear Fuel Disposal of the Olkiluoto (OL1-3) and Loviisa (LO1-2) Nuclear Power Plants	SKB [30]. Costs for management of the radioactive waste products from nuclear power production	METI [34]. Revision of the basic policy on specified radioactive waste final disposal and the specified radioactive waste final disposal plan	ONDRAFT/NIRAS [33]. SAFIR 2 report: safety assessment and feasibility interim report 2	Nirex [35]. Cost estimate for reference repository concept for UK high-level waste/spent fuel	SAPIERR II [36]. Strategic Action Plan for Implementation of European Regional Repositories: Stage 2. Work Package 3. Economic Aspects of Regional Repositories
Site exploration and improvement costs (repository development, site investigation, etc.)	8300	–	321	2086	56	1225	698
Engineering costs (underground and above ground facilities, excavation, repository construction, monitoring)	56,400	863	3423	21,864	1979	4322	9717–13,078
NW handling and storage operation and maintenance costs (expenses for labor, chemicals, surface and underground equipment maintenance, cost of energy to operate equipment, etc.)	20,250	2930	472	–	–	490	1451
Site closure and post-closure costs (site care, monitoring, etc.)	–	329	–	–	–	–	–
Other (research and development, administration costs)	11,200	–	1512	9079	–	1558	436
Total	96,180	4122	5728	33,066	2035	8483	12,303

Table 3
Comparative assessment framework for CO_2 and NW geological storage comparison.

Indicator	Unit
Technical performance	
Storage capacity	t CO_2/kWh; tHM/kWh
Storage depth	km/kWh
Time life for NW and CO_2 storage	Years/kWh
Market Assessment	(Score 0–5)
Technical Assessments for Regulatory Decisions	(Score 0–5)
Research and Development (R&D) Assessments	(Score 0–5)
Economic feasibility	
Levelized life-cycle cost of CO_2 or nuclear waste storage (investments and operation costs)	EURcnt/kWh
Market Assessment	(Score 0–5)
Environmental and human health impact	
Life-cycle GHG emission	CO_2 equiv. kg/kWh
Life-cycle environmental external costs	EURcnt/kWh
Life-cycle external human health costs	EURcnt/kWh
Life-cycle radionuclides external costs	EURcnt/kWh
Land use	ha/kWh
Social performance	
Life cycle technology-specific job opportunities	Person-year/kWh
Severe accidents perceived in future	(Score 0–5)
Potential of conflicts induced by energy systems	(Score 0–5)
Willingness of Non Governmental Organizations or citizens movement to act against a certain technology option	(Score 0–5)
Necessity of participative decision making processes for different kinds of energy systems	(Score 0–5)
Functional impact of energy infrastructure on environment	(Score 0–5)
Aesthetic impact of energy infrastructure on environment, etc.	(Score 0–5)

detailed life cycle data for full nuclear and fossil fuel with CCS chain. The data relevant to CO_2 and nuclear waste storage stage needs to be obtained from full fuel cycle data. The Ecoinvent data developed by PSI and other energy technology assessment studies will be used to obtained necessary information for relevant back-end technologies assessment in Lithuania. The Multi-criteria analysis can be applied for scoring of these back-end technologies.

The weighted scoring method, also known as 'weighting and scoring', is a form of multi-attribute or multi-criteria analysis. It involves identification of all the non-monetary factors or attributes that are relevant to the project. The method assigns numeric values to judgments, so both quantitative and qualitative inputs for decision making are easily handled. The core of weighted scoring method are the decision criteria, the allocation of weights to each of them to reflect their relative importance, and the allocation of scores to each option to reflect how it performs in relation to each attribute. The result is a single weighted score for each option, which can be used to indicate and compare the overall performance of a process alternative in non-monetary terms.

The main indicator for economic feasibility is costs assessment of the back-end technologies. Cost assessments will range from direct price comparisons to life cycle cost assessments. Life cycle costing is a holistic assessment of the comparative cost of options. The main cost categories for back-end technologies assessment are: (1) site exploration costs (site characterization, investigation, etc.); (2) engineering costs (site design and construction); (3) operation and maintenance costs (expenses for labor, chemicals, surface and subsurface equipment maintenance, cost of energy to operate equipment, etc.); (4) site closure and post-closure costs (closure costs, monitoring cots, etc.). These sub-cost categories consist of capital and operational expenditure. The Long-term financial indicators (e.g., net present value, internal rate of return, and profitability index) are also used seeking to determine levelized costs per kWh of electricity produced. The main indicator for economic feasibility assessment of back-end technologies selected is the cost of CO_2 or nuclear waste storage per kWh of electricity produced.

4. Carbon dioxide geological storage costs in Lithuania

Seeking to assess carbon dioxide geological storage costs feasible carbon dioxide storage options need to be reviewed in Lithuania.

4.1. Carbon dioxide storage options in Lithuania

Deep saline aquifers are by far the most popular proposal for large-scale CO_2 storage. These are water-saturated porous layers in the subsurface of sandstone or limestone, at present not used for any other purpose. The high water salinity renders these layers unsuitable for use as drinking water or for watering plants. Depending on the formation pressure and temperature, CO_2 can be stored either as compressed gas or in a supercritical state. CO_2 can be stored in the hydrodynamic traps (structural, stratigraphic). Some of the injected CO_2 will dissolve in water or will be trapped by matrix particles. The capability of an aquifer to transmit and store CO_2 is controlled by the depositional environment, structure, stratigraphy and pressure/temperature conditions. Critical factors are [41,42]: the regional water flow system; the thickness, lateral extent and continuity of the aquifer; the tightness of the seal above the aquifer, including the faults and the capability of overburden layers above the reservoir seal to delay or diffuse leakage.

Only two large aquifers of the Baltic States meet requirements listed above, i.e., the Lower–Middle Devonian (Pärnu–Kemeri formations) and Middle Cambrian aquifers buried to depths exceeding 800 m in the central and western parts of the Baltic basin [41].

The Cambrian reservoir is distributed in all Baltic countries. Its depth varies from outcrops in Estonia to more than 2 km in West Lithuania. The depth of the reservoir exceeds 800 m in West Lithuania and in the Baltic offshore. The reservoir is composed of quartz sandstones with subordinate siltstones and shale. The thickness of the aquifer is in the range of 20–70 m [42]. Due to considerable variations in depth and temperature, the porosity of sandstones changes drastically across the basin, from 20% to 30% in the northern and eastern shallow part of the basin to less than 5% in the central and western parts of the basin. The Middle Cambrian represents a reliable seal rock.

The Pärnu–Kemeri aquifer is distributed in the central part of the basin. Its depth exceeds 800 m only in West Lithuania and the south eastern part of the Baltic offshore where it reaches 1100 m. The aquifer is composed of arkosic sandstones containing siltstone and shaly layers. The net-to-gross ratio is of order of 0.7–0.8. Average porosity of sandstones is 26%; permeability is in the range of 0.5–2 D. Total thickness of the aquifer varies from 100 to 160 m in West Lithuania. There are 3 potential geological aquifer structures in South-West of Lithuania: Vaskai 8.7 Mt), Syderiai (21.5 Mt), D11(11.3) which can store totally 41.5 Mt of CO_2 [40].

The solubility trapping is not restricted to particular structures. The solubility of CO_2 ranges from 2% to 6%, depending on the brine salinity, temperature, and pressure. However, the large volume of a regional-scale aquifer provides an attractive alternative for CO_2 disposal. The solubility trapping potential has been calculated using the approach presented in [40]. It accounts for the brine salinity, temperature, pressure and reservoir properties that vary considerably across the Baltic basin. The solubility of CO_2 in Cambrian formation water varies from 25–30 kg/m^3 in West Lithuania to 40–50 kg/m^3 and in East Lithuania. The CO_2 storage potential changes westwards from 0.4 Mt/km^2 to 0.05 Mt/km^2. The calculated total solubility trapping capacity is as high as 11 Gt of CO_2 within the area of the supercritical state of the carbon dioxide [40].

The Pärnu–Kemeri aquifer is characterized by better reservoir properties, but has a smaller area of extent than the Middle Cambrian reservoir. CO_2 solubility ranges from 36 kg/m^3 in the deep part of the basin to 60 kg/m^3 in the shallow periphery of the basin. In West Lithuania the storage capacity of the reservoir is about 1 Mt of CO_2 in 1 km^2 area. The total onshore potential of this formation is estimated as high as 1 Gt of CO_2The calculated total solubility trapping capacity in Lithuania is 5.5 Gt. The Pärnu–Kemeri aquifer onshore storage potential is 3 Gt of CO_2. The Cambrian aquifer onshore storage potential is 2.5 Gt [40].

The mineral trapping that involves a series of interactions between the formation mineralogy and CO_2-enriched aquifer waters, can convert CO_2 to carbonate, an immobile and harmless mineral that will be stored for millions to hundreds of millions of years. Reactions with Ca/Mg/Fe-bearing silicate minerals are the most promising for carbon sequestration because these silicates neutralize the added acidic CO_2 and provide alkali metals that trap CO_2 through the precipitation of carbonate [41,42].

The Middle Cambrian reservoir comprises quartz sandstones that are practically not reactive to carbon dioxide. The Pärnu–Kemeri sandstones contain clay admixture (up to 10%) and feldspar grains (up to 15%). Therefore they have a potential for permanent immobilization of carbon dioxide in mineral form. Assuming the rock capacity of 10 kg/m^3 [41], the sequestration potential can be evaluated to reach 5.6 Gt of CO_2 (onshore) [40].

In Lithuania, ten oil fields are presently exploited. The size of oil fields ranges from 16,000 t to 1,400,000 t of the recoverable oil. The storage potential of the largest oil fields in West Lithuania reaches 2 Mt of CO_2. The total potential in Lithuania is estimated at 7.6 Mt of CO_2. No coal seams exist in the Baltic area, but thin lignite layers have been identified in Jurassic succession of Lithuania. Salt has accumulated in the Zechstein lagoon in the Kaliningrad district, while only one small salt pillow is found in Southwestern Lithuania [40].

Total CO_2 storage potential in Lithuania amounts to about 11.21 Gt however the current well developed CO_2 storage technologies such as structural trapping has very low potential in Lithuania – 41.5 Mt.

4.2. Carbon dioxide disposal concept

Only two large aquifers of the Baltic States meet requirements set for effective carbon dioxide storage, i.e., the Lower–Middle Devonian (Pärnu–Kemeri formations) and Middle Cambrian aquifers buried to depths exceeding 800 m in the central and western parts of the Baltic basin. The Cambrian reservoir is distributed in all Baltic countries. Its depth varies from outcrops in Estonia to more than 2 km in West Lithuania. The depth of the reservoir exceeds 800 m in West Lithuania and in the Baltic offshore. The reservoir is composed of quartz sandstones with subordinate siltstones and shale. The thickness of the aquifer is in the range of 20–70 m. There are 3 potential geological aquifer structures in South-West of Lithuania: Vaskai 8.7 Mt), Syderiai (21.5 Mt), D11 (11.3 Mt) which can store totally 41.5 Mt of CO_2 [40]. The Syderiai has the biggest potential therefore this option was selected for the assessment of CO_2 storage costs in Lithuania. The main characteristics for CO_2 storage in Syderiai geological structure are presented in Table 4. The emissions from the main power plants makes about 5.5 Mt/year.

There are no costs estimated developed for CO_2 storage in Lithuania therefore the methodology developed by United States Environmental Protection Agency [23,24] will be applied for assessing carbon dioxide storage costs in Syderiai geological structure. The benefit transfer approach based on the rate between USA and Lithuania GDP/capita adjusted at PPP will be applied to transfer estimated developed for USA to Lithuania.

Table 4
The main characteristics for CO_2 storage in Syderiai geological structure in Lithuania.

No.	Parameter	Value or description
1	Power plant type, fuel and capacity (MW)	Thermal power plant, (natural gas and HFO) capacity 1800 MW
2	Average annual electricity production at power plant (GWh)	2938
3	Power plant utilization rate (% of the year)	65
5	Average CO_2 emissions per year (t)	6
6	CO_2 capture rate (%)	90
7	CO_2 storage concept (EOR, coal bed methane recovery, Saline aquifers, etc.)	Saline aquifer
8	Seismicity	3-D
9	CO_2 storage capacity at 100% storage efficiency (m^2)	100,000,000
10	Stratigraphy	Middle Cambrian
11	Lithology	Sandstone
12	Area of well spacing (km^2)	26 (16.2 ml)
13	Number of injection wells	3
14	Total number of monitoring wells	1
15	Injection pipe diameter (m)	0.14
16	Injection depth (m)	1458
17	Reservoir thickness (m)	57
18	CO_2 supply pressure (MPA)	15.3
19	Reservoir horizontal permeability (mD)	400
20	Storage efficiency factor	0.3
21	CO_2 storage capacity (Mt)	21.5
22	Injection period (years) (during 4 years of plant operation the storage capacity will be utilized)	4

4.3. Cost categories and total costs

The main costs components for CO_2 storage applied in EPA studies [23,24] are the following: site characterization, injection well construction, monitoring, well operation, mechanical integrity test, area of review and corrective actions, site closure (post injection well plugging and site care), financial responsibility and administrative costs. The same cost components will be applied for CO_2 storage assessment at Syderiai.

The cost of site characterization is highly dependent on the requirements of the regulatory regime to which the project is subject. However, given that CO_2 should be isolated from the atmosphere for long timescales, it would be prudent to characterize the subsurface over the area which the injected CO_2 is likely to spread over a set time horizon to ensure that conduits to the surface, natural or otherwise, do not exist. Therefore, the main factor affecting the cost of site characterization will be the area of review.

McCoy [19] suggests the approximate costs associated with characterizing this area to be \$38,610/km^2 for geophysical characterization (3-D seismic); \$3,000,000 to drill and log a well; and an additional 30% of these total costs for data processing, modelling, and other services. One well would be required for every 65 km^2 of the review area [19]. These costs for Syderiai storage would make 1,003,860 USD for geophysical investigation and 30,000,000 USD for drill well plus 9,000,000 USD additional costs related to data processing and modelling. The total costs of site characterization make 3.2 mill. USD (2008). The site characterization costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 1.4–4.4 mill. USD (2008) [24]. Based on Table 2 [24] which presents unit costs for site characterization (per site and per square mile surveyed) developed for USA the site characterization costs for Syderiai storage (surveyed area of 16.2 miles) makes 1.9 mill. USD (2008).

Design of the monitoring wells is included under the monitoring section. Injection well construction costs include development of standard plans associated with current Underground Injection Control regulations (e.g., the drilling and casing plan, wellhead

equipment plan, and down hole equipment selection), as well as pre-operational logging, sampling, and testing. Costs are specified as a base cost per site and a cost per injection well in Table 4 [23]. The injection well construction costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 9.1–9.7 mill. USD (2008) [24]. The costs of injection well construction for Syderiai storage are evaluated 9 mill. USD (2008) based on unit costs presented in Table 4 [23].

Once injection begins, a programme for monitoring of conditions in the injection zone and CO_2 distribution is required. This is needed in order to: manage the injection process; delineate and identify leakage risk or actual leakage, verify and provide input into computational models and provide early warnings of failure. According APA [23] a monitoring components must, at a minimum, include the following: analysis of the carbon dioxide stream; installation and use of continuous recording devices to monitor injection pressure, rate, and volume; the pressure on the annulus between the tubing and the long string casing; and the annulus fluid volume added; corrosion monitoring; monitoring of ground water quality and geochemical changes above the confining zone(s); a demonstration of mechanical integrity; a pressure fall-off test; testing and monitoring to track the extent of the carbon dioxide plume and the presence or absence of elevated pressure and any additional monitoring required by responsible institution. The monitoring costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 0.52–1.26 mill. USD (2008) [24]. Based on Table 3 [24] presenting unit costs for monitoring the assessed monitoring costs for Syderiai storage makes about 1 mill. USD (2008).

This cost category includes those cost elements related to the operation of the injection wells, including measuring and monitoring equipment, electricity costs, O&M costs, pore space costs, repair and replacement of wells and equipment, and estimated costs for the possibility of failure at the site and the need to relocate a geological sequestration operation. The operation costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 1.2–2.1 mill. USD (2008) [24]. Based on Table 6 [23] the costs of corrective actions for Syderiai storage makes about 1 mill. USD.

Owners or operators of CO_2 injection wells must periodically evaluate well integrity to ensure mechanical soundness, lack of corrosion, and ability to sustain pressure. There are several such tests that are typically used, and they include both pressure tests and wireline logs. These technologies are well established and have been used for decades for underground injection operations. The mechanical integrity test costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 13,215–13,500 USD (2008) [24]. Based on Table 7 [23] the costs of corrective actions for Syderiai storage makes about 0.013 mill. USD (2008).

Corrective actions cost includes fluid flow and reservoir modelling to predict the movement of the injected CO_2 and pressure changes during and after injection. It also includes those cost elements pertaining to the identification, evaluation, and remediation of existing wells within the area of review. The corrective actions for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 0.53–1.1 mill. USD (2008) [24]. Based on Table 5 [23] the costs of corrective actions for Syderiai storage makes 0.56 mill. USD.

After the injection phase has ended, the owner or operator must close the site in a safe and secure manner and monitor the site during the post injection period. This involves the plugging of injection wells, removal of surface equipment, and land restoration. It also includes long term requirements for monitoring the site to ensure safety and to confirm that the CO_2 moved as expected in the subsurface. The site closure costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 0.17–0.9 mill. USD (2008) [24]. Based on Table 9 [23] the costs of corrective actions for Syderiai storage makes about 0.18 mill. USD (2008).

All owners and operators of geological sequestration projects will incur one-time costs that include time for staff to become familiar with geological sequestration rules and to train employees on these activities. To ensure that resources are available to protect storage from endangerment, USA rule identifies qualifying financial instruments, the time frames over which financial responsibility must be maintained, procedures for estimating the costs of activities covered by the financial instruments, procedures for notifying the responsible institution of adverse financial conditions, and requirements for adjusting cost estimates to reflect changes to the project plans. The financial responsibility and administrative costs are country specific and depends on national laws. These costs for pilot project in saline aquifers for different regulatory regimes in USA are evaluated in range 885–1327 USD (2008) [23]. As these costs are negligible com paring with other items they are skipped from assessment of costs of CO_2 storage at Syderiai storage.

The total costs of CO_2 storage are generalized in Table 5. The costs assessed in USD (2008) were converted into USD (2010) by taking into account the exchange rate and annual inflation rate 1.4% over the period 2008–2010 and the benefit transfer approach was used to apply USA cost estimated for Lithuania in 2010. The ratio of GDP/capita adjusted at PPP in Lithuania and USA in 2010 was 15,900/47,400 USD = 0.335 therefore this coefficient was applied to adjust USA values to Lithuanian conditions.

As one see from Table 5 the total costs of carbon dioxide storage for Syderiai make 14.1 mill. USD (2010) however in the case of benefit transfer from USA to Lithuania these costs would make 5 mill. USD.

5. Nuclear waste storage costs in Lithuania

Seeking to assess nuclear waste storage costs in Lithuania the disposal concept needs to be defined from several possible nuclear waste disposal options in Lithuania.

5.1. Nuclear waste disposal options in Lithuania

It has been universally acknowledged that in terms of environment protection the only cohesive and safe way of final disposal of spent nuclear fuel and other long-lived high-level radioactive waste is in deep geological repositories. The final disposal of this type of waste in deep geological repositories may be justified by the usage of stable geological environment. Radioactive waste is isolated by several passive barriers that reinforce and complement one another. Safety of the repository will remain sufficient even if deficiencies occur in one of the barriers or it fails to perform its functions. Safety of humans and the environment will be ensured by using natural barriers, that is old, stable rocks laying at large depths, together with engineered barriers. The engineered barriers are adjusted to the environment of the repository and designed in such a way as to isolate the radioactive waste stored in the repository and prevent it from outspread, while there is no need for post-closure surveillance of the repository.

Therefore the repositories for disposal of SNF and high-level waste generally rely on a multi-barrier system to isolate waste from the biosphere. The multi-barrier system usually comprises a natural geological barrier and engineered barrier system [43]. The host rock types currently under investigation are salts (in either salt domes or bedded formations), granite and similar crystalline rocks, argillaceous rocks, tuff and basalt. The most investigated host rocks to date are crystalline rocks.

Table 5
Cost components for CO_2 storage in Lithuania.

No.	Cost component	Total mill. USD (2008)	Total mill. USD (2010)	Total mill. USD (2010) by applying benefit transfer
1	The costs of programme administration, R&D, site characterization costs	1.9	1.95	0.7
2	Engineering costs (injection well construction)	9	9.25	3.1
3	Monitoring costs	1	1.03	0.34
4	Well operation costs including mechanical integrity test, area review and corrective actions costs	1.6	1.65	0.55
5	Site closure and post-closure costs (site care, monitoring, etc.)	0.2	0.21	0.1
	Total	13.7	14.1	4.75

The overview of the geological structure of Lithuania was carried out for feasibility studies in terms of suitability for a deep geological repository. Several major candidates of geological media (clayey formations, rock salt and anhydrite formations, crystalline basement rocks) were selected for future considerations (Table 6).

As a result of the overview, four clayey formations perspective as a host rock were distinguished in the sedimentary cover of Lithuania. They are represented by the Lower Cambrian, Lower Silurian, Middle Devonian and the Lower Triassic sequences. The most perspective from clayey formations is Lower Triassic sequences. The Lower Cambrian Formation occurs only in the eastern part of Lithuania (proximity to the INPP region). Lower Triassic sequence occurs only in southwest Lithuania (quite far from the INPP) [44].

The Upper Permian anhydrite and rock salt of the Prieglius Formation occurred at a depth of 150–790 m in a more than 12,000 km^2 area of South and Southwest Lithuania. Studies have showed that the suggested salt domes in fact are anhydrite and gypsum bodies. Therefore, the Usėnai dome was considered as the only salt body known in Lithuania. After feasibility studies it was concluded that rock salt media could not be regarded as a highly potential alternative for SNF.

Crystalline basement used for final disposal of spent nuclear fuel and long-lived radioactive waste is the most examined geological medium in the world. An additional advantage of this medium is that this geological formation may be found at lower or higher depths everywhere. In Lithuania there are quite large blocs of crystalline basement not much affected by tectonic processes lying at a depth suitable for a deep geological repository to construct. Such blocs are a promising location for constructing a deep geological repository. In Lithuania the crystalline basement is covered by sediments the thickness of which varies from 200 to 300 m in south-east Lithuania to 2000 m in the Baltic seacoast. With the use of the state-of-the-art technologies, it is possible to construct shafts in rocks of crystalline basement and to bore 150–500 m long tunnels at a depth of some 500 m in which containers with spent fuel may be placed. All gaps between the copper containers with fuel and the rocks would be loaded by special impervious clay (bentonite).

Clayey rocks are also a promising medium since clay is quite impervious, distinguished by its properties of sorption. Clay, however, is not so steady and less stable than rocks of a crystal base. Therefore, to construct a repository in the medium of clay would be a much harder task than to do so in the rocks of crystalline basement. The lowermost Cambrian Blue Clays formation is one of the three most prospective geological formations. Its quality is somewhat lower than that of the crystalline basement and Triassic clays. However, it has some important advantages, such as distribution beneath and close to the Ignalina NPP. The thickness of the clay package reaches 115 m, the depth ranging from 200 to 1010 m. The thickest and lithologically most homogeneous succession is identified in the Ignalina NPP area. The best prospects for SNF in Lithuania are the crystalline basement in the South-eastern Lithuania. Though clay is considerably less permeable than crystalline basement rocks, however, it is less stable and construction of a repository in clay is much more difficult than in crystalline basement rock [45,46].

Table 6
Potential geological formations for spent nuclear fuel geological disposal in Lithuania.

Age	Geological media	Depth (m)	Thickness (m)
Middle Devonian	Dolomite	95–190	80
Silurian	Marl	166–316	40
Cambrian	Clayey	340–520	70–110
Proterozorian crystalline basement	Granite	700–800	

5.2. Nuclear was disposal concept

Some 22,000 nuclear fuel assemblies, an equivalent of approximately 2500 t of uranium, were used at the Ignalina NPP throughout its operation. All these assemblies should be stored about 50 years and after that disposed of. In order to manage and dispose of spent nuclear fuel (SNF) and long-lived radioactive waste from Ignalina NPP to deep geological repository, that is assumed to be in operation since 2041. Several potential geological formations for long-lived high level radioactive waste storage are available in Lithuania: crystalline basement, clay, anhydrite, etc. Research conducted over the recent years shows clay and granite type crystalline basement formations to be potentially the most suitable. The best prospects of the crystalline basement appear to be related to the southeastern Lithuania where the basement rocks are overlain by a relatively thin (200–300 m) sedimentary cover [47].

Disposal concept for RBMK-1500 spent nuclear fuel (SNF) in crystalline rocks in Lithuania is based on Swedish KBS-3 concept with SNF emplacement into the copper canister with cast iron insert. The bentonite and its mixture with crushed rock are also foreseen as buffer and backfill material. Taking into account the results of the criticality, dose rate assessment and thermal calculations it was proposed to load 32 half-assemblies of RBMK-1500 SNF in one disposal canister. Based on preliminary assessment the reference canister would be of 1050 mm diameter and 4070 mm length. For Lithuanian SNF disposal purposes about 1400 canisters should be employed [43].

The lay-out and design of a repository depend on the properties of radioactive waste and geological media. As in crystalline rock water flows are more abundant than in clay formations, a stronger canister is required to ensure the safety functions. Copper canister having very high corrosion resistance is therefore recommended for the disposal of SNF in crystalline basement. Canisters containing SNF are to be lowered via shafts and tunnels into 150–500-m-long tunnels drilled at a depth of 300–500 m. The length of 250 m of SNF emplacement tunnels is accepted at this stage of investigations. All the spaces between SNF canisters and rock are to be sealed with special impermeable clay (bentonite) of 0.35 m thick surrounding

Table 7
Key performance parameters for NW storage.

No.	Parameter	Value or description
1	Nuclear power plant type, fuel and capacity (MW)	2 RBK-1500 MW reactors, uranium
2	Electricity produced during the life-time of nuclear power plant (GWh)	3079
3	Average utilization rate (% of the year)	80
4	Life time of power plant (years)	21
5	Nuclear Fuel waste accumulated (t HM (heavy metal)/lifetime)	2436
7	Nuclear waste storage type or repository concept	Repository concept developed in Sweden for SNF disposal of in the crystalline rocks (KBS-3V)
8	Location, rock type	Crystalline rock
9	Underground depth of repository (m)	300–500
10	The area of isolating rock zone (km^2)	0.4
11	Type and amount of containers used	2400 copper canister with cast iron insert
12	Natural barriers	Granite
13	Man-made barriers	Bentonite
14	The amount of nuclear waste to be stored (tHM) (heavy metal)	7945

it are vertically emplaced in the crystalline rocks at the depth of 500 m.

The repository for spent nuclear fuel consists of a large number of parallel deposition tunnels with deposition holes bored in the bottom. The deposition tunnels are connected by main tunnels for transport of fuel canisters, materials and personnel, as well as tunnels for ventilation and utility lines. The main tunnels are connected to central area underground and via tunnels and shafts to the ground surface. The height and width of the main tunnels are assumed to be 6.8 and 7 m respectively. The distance between two tunnels is 25 m. Transport tunnels connect these deposition tunnels. Apart from the canister transfer shaft, the facility is connected to the ground surface by a personnel shaft and a working shaft. The canister spacing is 6.0 m and the tunnel spacing is 40 m. After deposition, the tunnel above the deposition hole will be backfilled with a mixture of bentonite clay and crushed rock. This disposal method is known as KBS-3V [30,32] and developed in Sweden for SNF disposal in the crystalline rocks. The tunnels of the repository designed to accommodate all the SNF of Ignalina NPP are to occupy an area of some 0.4 km^2 [43,44]. The main parameters of SNF disposal in Lithuania are presented in Table 7.

5.3. Cost categories and total costs

The general stages for SNF storage are: pre-operation, operation and post-operation phases [1]. The pre-operation phase include planning, initial research and administration; site investigation and characterization, development and construction of repository and other above-ground facilities including encapsulation plant. Operational phase includes transportation, encapsulation and emplacement of SNF. Post-operation phase includes decommissioning of above ground facilities and closure and monitoring of underground repository. Also costs of programme administration are incurred during all phases. R&D costs are also included in pre-operation phase.

In pre-operation stage the main cost items are related with costs of programme administration, planning, initial research costs, site investigation, characterization and selection costs, costs of selection and conceptual design of repository, land acquisition costs and construction costs. Construction costs include construction of underground facility and above-ground facilities including encapsulation plants, on site infrastructure including transportation system, administration buildings, etc.

In operation stage the main cost items are related with programme administration; spent nuclear waste transport, handling, purchases of canisters, buffer material production, encapsulation and emplacement of waste packages into a repository.

During the post-operation phase the main cost items include administration costs; costs decommissioning of the above-ground facilities, restoration of surface area, closure of repository and monitoring costs.

A cost estimation for model case of deep repository in Lithuania has been carried out. This preliminary cost assessment is based on experience accumulated during development Swedish KBS-3V concept [30,32] and applied to Lithuanian case. In order to give some guaranties to cover the loss as a result of future unforeseen events reasonable additional costs (cost variations) are included into the calculations. The same methodology as in Sweden for cost assessment of SNF disposal has been employed [46]. The input data for the calculations are obtained from "most likely" costs or so-called "reference costs" by means of conventional (deterministic) calculation based on functional description of each facility resulting in layout drawings, equipment lists, personnel forecasts, etc., under established fixed conditions but without allowances for variations and uncertainties. In order to give some guaranties to cover the loss as a result of future unforeseen events reasonable additional costs (cost variations) are included into the calculations. An influence of the chosen variations on the costs is evaluated. The result gives a mean value of the cost (future costs) and the standard deviation of the cost for the chosen 50% degree of confidence [47]. The input data for the calculations are obtained from "most likely" costs or so-called "reference costs" for each calculation object and for the total [48,49]. The reference costs are calculated on basis of the reference scenario by means of conventional calculation under established fixed conditions. Traditional deterministic calculation is based on functional description of each facility, equipment lists, personnel forecasts, etc., but without allowances for variations and uncertainties. A base cost is calculated for each cost item, including: quantity-related costs; non-quantity-related costs and secondary costs. Quantity-related costs are costs that can be calculated directly with the aid of design specifications and with knowledge of unit prices, e.g., for concrete casting, rock blasting and operating personnel. These non-quantity-specified costs can be estimated with good accuracy based on experience from other similar projects. Secondary costs include costs for administration, design, procurement and inspection as well as the costs for temporary buildings, machines, housing, offices and the like [47–49].

First of all planning, preliminary research and administration costs are discussed. Lithuanian Radioactive Waste Management Agency (RATA) is engaged in permanent administration activities related to disposal of SNF and long-lived waste. It is foreseen that approximately 20 persons from RATA's staff and about 150 people from outside of RATA will be involved in waste handling and research works. The costs of planning, administration and preliminary research are evaluated in range 200–224 mill. Lt (2005).

Main purpose of RD&D programme is to collect necessary information, knowledge and data to realize final disposal of spent nuclear fuel and other long-lived radioactive waste. Foremost the RD&D work is focused on measures necessary to build an encapsulation plant for SNF and deep repository for encapsulated fuel and long-lived operational and decommissioning waste from Ignalina NPP. In addition safety assessments are included into RD&D activities. The costs of RD&D programme and safety analysis are evaluated in the range of 859–1064 mill. Lt (2005) [47].

Table 8
Cost components for spent nuclear waste storage in Lithuania.

No.	Cost component	Capital expenditure (mill. Lt) (2005)	Operational expenditure (mill. Lt) (2005)	Total (mill. Lt) (2005)	Total (mill. USD) (2010)
1	The costs of programme administration, R&D, site exploration and improvement costs (repository development, site investigation, etc.)	1393–1709	–	1393–1709	~500–600
2	Engineering costs (underground and above ground facilities, infrastructure construction, excavation, repository construction, monitoring,)	2893–4007		2893–4007	~1000–1400
3	NW handling and storage operation and maintenance costs (expenses for labor, chemicals, surface and underground equipment maintenance, cost of energy to operate equipment, etc.)		2244–2875	2244–2875	~800–1000
4	Site closure and post-closure costs (site care, monitoring, etc.)	–	–	–	–
	Total	4286–5716	2244–2875	6530–8591	~2300–3000

The basic objective of site characterization process is to select a suitable site for disposal of SNF and long-lived waste and to demonstrate that selected site in conjunction with deep repository design and radioactive waste package has properties which provide adequate isolation of radionuclides from accessible environment for desired periods of time. The sitting of the deep repository will be performed in stages with feasibility studies, site investigation and detailed characterization. First, the basic functional requirements for the new facility are reasonably defined. Next, reference projects having similar characteristics and for which cost values are available are identified. The costs can be deduced from the reference cases using correlation techniques and simple linear relationships with respect to some engineering parameters such as size and power. The cost estimate for site characterization is based on the Swedish methodology and makes 334–421 mill. Lt (2005) [47].

Construction starts from setting of the system needed for transportation of SNF from interim storage (Ignalina NPP site) to encapsulation plant (deep repository site). It is intended to use the same system for transportation of immobilized long-lived waste from interim storage to deep repository. It is assumed that deep repository will be about 120–200 km from INPP but not more than 350 km (largest distance across Lithuania). Transportation by rail from Ignalina to the area of deep repository will be necessary mainly. Investments in transportation system makes 239–309 mill. Lt [47].

Before spent fuel is emplaced in a deep repository it must be encapsulated in canisters. One canister contains 32 RBMK fuel half-assemblies. It is estimated that approximately 1400 copper canisters of Swedish type will be necessary to produce for deposition of SNF from Ignalina NPP. It is assumed that a capacity of the plant will be 50 canisters per year. Encapsulation is planned to take place in the area of deep repository. The plant will be dismantled and decommissioned at the end of deposition period of spent nuclear fuel. The costs of construction of encapsulation plant are evaluated in range of 851–1188 mill. Lt. The costs of decommissioning are included in investments costs.

It is assumed that the spent nuclear fuel of D, E and F classes will be packaged and stored into concrete containers measuring ($L \times W \times H$): 3 m × 1.65 m × 1.25 m, and volume of 6.2 m without grouting or immobilization for interim storage of long-lived waste on the INPP site. The investments into facilities above ground (operation sites) for deep repository makes 701–947 mill. Lt (2005). The investments into underground facilities (shafts, access tunnels and service area makes 945–1366 mill. Lt (2005). The investments into other underground facilities such as deposition panels makes 105–146 mill. Lt (2005). The investments into deep repository makes 43–51 mill. Lt (2005). These all investment costs include costs of closure and decommissioning costs as well. The investment cost into interim storage for SNF is not included in cost estimates [47].

The costs for operation, maintenance and decommissioning of interim storage (including costs for the disposal containers and waste conditioning) have been estimated with the calculations of costs for deep repository.

The operation and maintenance of transportation system makes 73–90 mill. Lt (2005). Operation and maintenance costs for encapsulation plant are evaluated in range of 317–410 mill. Lt (2005). The operation and maintenance costs for canisters makes 295–402 mill. Lt (2005). The operation and maintenance costs of above ground facility makes 565–722 mill. Lt (2005). The operation and maintenance costs for underground facilities (shafts, access tunnels and service area) – 48 access tunnels and service area50 mill. Lt (2005). The costs of backfill makes 129–171 mill. Lt (2005). O&M costs for deposition panels – 38–50 mill. Lt(2005). The costs of backfill makes 129–171 mill. Lt (2005). The O&M costs for deep repository including backfill costs makes 343–401 mill. Lt(2005) [47].

The costs of closure, verification and monitoring are included in investment costs of above ground and underground facilities and deep repository of SNF.

The total costs of spent nuclear fuel storage are generalized in Table 8. The costs assessed in Litas (2005) were converted into USD (2010) by taking into account the exchange rate and annual inflation rate over the period 2005–2010.

Table 8 shows the estimated future costs of 50% probability for the waste management system according to the reference scenario. The costs for different facilities are reported here in the following items (cost categories): investment, operation and maintenance plus decommissioning and backfill. Investment costs normally only include those costs that arise before a facility is put into operation. Investment costs normally only include those costs that arise before a facility is put into operation. The difference of approximately 32% (~2200 mill. Lt) of the future costs in comparison to reference costs gives guaranties of 50% to cover the loss due to future unforeseen events and uncertainties (cost variations) estimated in the calculations. It was identified that the impact of general variations on estimated costs is most important.

Table 9
Country specific summary: comparing SNF and CO_2-storage costs in Lithuania.

Storage	Implementation	Evaluation method	Evaluation method	Disposal concept	Total costs (mill. USD) (2010)	Storage capacity (t) (HM or CO_2)	Disposal costs/t HM or co_2 (USD) (2010)	Electricity generated during life time or during injection period (mill. kWh)	Costs/kWh (UScnt) (2010)
SNF	Planned	Based on study conducted	Based on study conducted	KBS-3V	2300–3000	7945	289,490–377,596	307,900	0.97
CO_2	Research	Based on own assessment	Based on own assessment	Saline aquifer	4.8	21,500,000	0.22	11,752	0.04

6. Comparative assessment of nuclear waste and CO_2 storage costs

The comparative assessment of SNF and CO_2 storage in Lithuania is presented in Table 9.

As one can see from Table 9 the costs of spent nuclear fuel geological storage in Lithuania are significantly higher comparing with carbon dioxide storage costs. Also comparing total nuclear waste storage costs with results of other studies conducted in several countries (Table 2) one can conclude that in Lithuania they are similar to Sweden, Belgium and Finland costs but significantly lower than in USA and Japan as different disposal concepts have been applied in Europe and USA and Japan.

7. Conclusions

1. The framework for comparative assessment CO_2 and NW geological storage technologies consists of technical, economic, social and environmental performance indicators and allows to compare energy back-end technologies by applying life cycle approach and using available databases for energy technologies assessment. The most challenging task is related with the separation of information and life cycle data for storage stage in full fuel chain of nuclear and fossil fuel with CCS.
2. The main economic feasibility indicators for back end technologies assessment consists of CO_2 and NW geological storage costs per kWh of electricity produced.
3. A wide range of approaches are applied to the development of cost estimates for carbon dioxide and nuclear waste geological storage depending on the primary objective of study. Calculation methods vary by country and region.
4. There is a wide cost range for carbon dioxide storage within each case, the high cost scenario being up to 10 times more expensive than the low cost scenario. This is mainly due to natural variability between storage reservoirs (i.e., field capacity and well injectivity) and only to a lesser degree to uncertainty in cost parameters. Despite this, the following trends stand out: onshore is cheaper than offshore. Depleted oil and gas fields are cheaper than deep saline aquifers (even more so if they have reusable legacy wells). The highest costs, as well as the widest cost range, occur for offshore deep saline aquifers.
5. There are no plans in Lithuania to develop CCS projects. Just preliminary estimates of CO_2 storage potential were evaluated in Lithuania. There are no cost estimates for CO_2 storage developed for Lithuania. The Syderiai geological structure having highest potential for CO_2 storage was selected for CO_2 storage costs assessment in Lithuania.
6. A wide variety of approaches are applied to the development of nuclear waste storage cost estimates. The cost studies were performed for the following nuclear waste repositories: Yucca Mountain in USA; the final nuclear waste repository Olkiluoto and Loviisa in Finlad and Forsmark in Sweden. The costs are assessed for nuclear waste repositories in Belgium, UK, Japan and multi-country repository in EU. The highest costs of final nuclear waste storage are in USA, following Japan. The lowest costs are found in Belgium, Finland and Sweden.
7. Lithuania has closed Ignalina NPP in 2009 and is considering SNF storage. Therefore the costs of SNF storage were assessed based on the studies conducted in Lithuania and CO_2 storage costs were evaluated in this report by applying cost model and unit costs developed by United States Environmental Protection Agency because of the lack of information on CO_2 storage costs in Lithuania.
8. The comparative cost analysis of SNF and CO_2 storage in Lithuania indicated that SNF storage costs are almost 10 times higher than CO_2 storage costs per electricity produced.

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